NANOSCALE ELASTIC-PROPERTY MAPPING WITH CONTACT-RESONANCE-FREQUENCY AFM

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...working with industry to develop and apply technology, measurements, and standards

Introduction and Motivation

- Mechanical properties are critical in many applications
  - predictive modeling of complex systems
  - performance and reliability
- Increasing need for information on the *nanoscale*
- Existing methods not optimal (too big, destructive, qualitative, ...)
- *Imaging* – visualization – increasingly important
  - multiple materials integrated at micro-, nanoscale
  - failure often due to local property variations

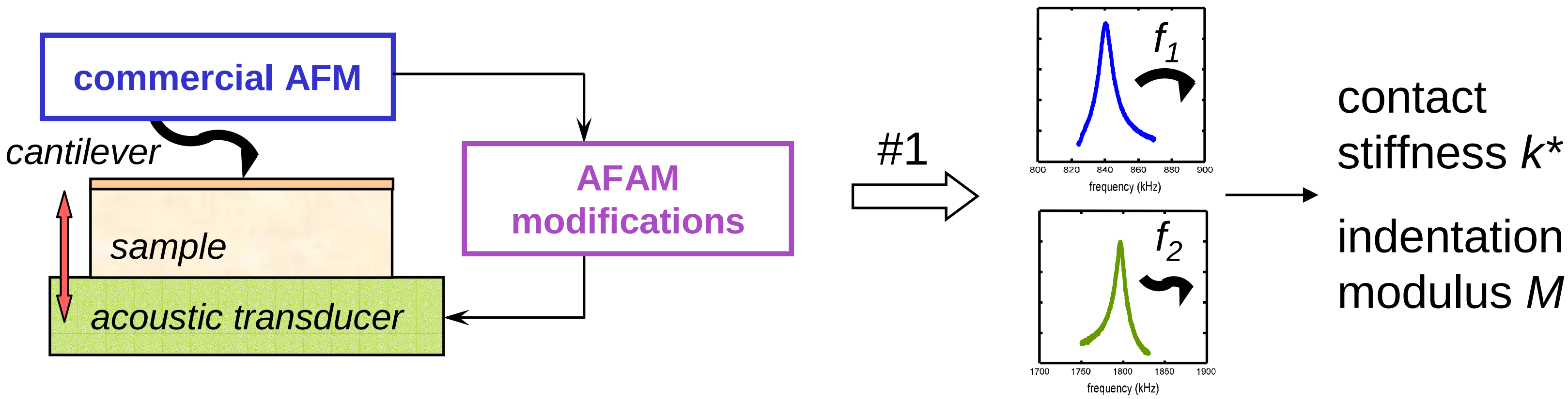
Objective:

Develop AFM methods for quantitative elastic-property imaging

Approach based on atomic force acoustic microscopy (AFAM)

Nanoscale Elastic Measurements with AFAM

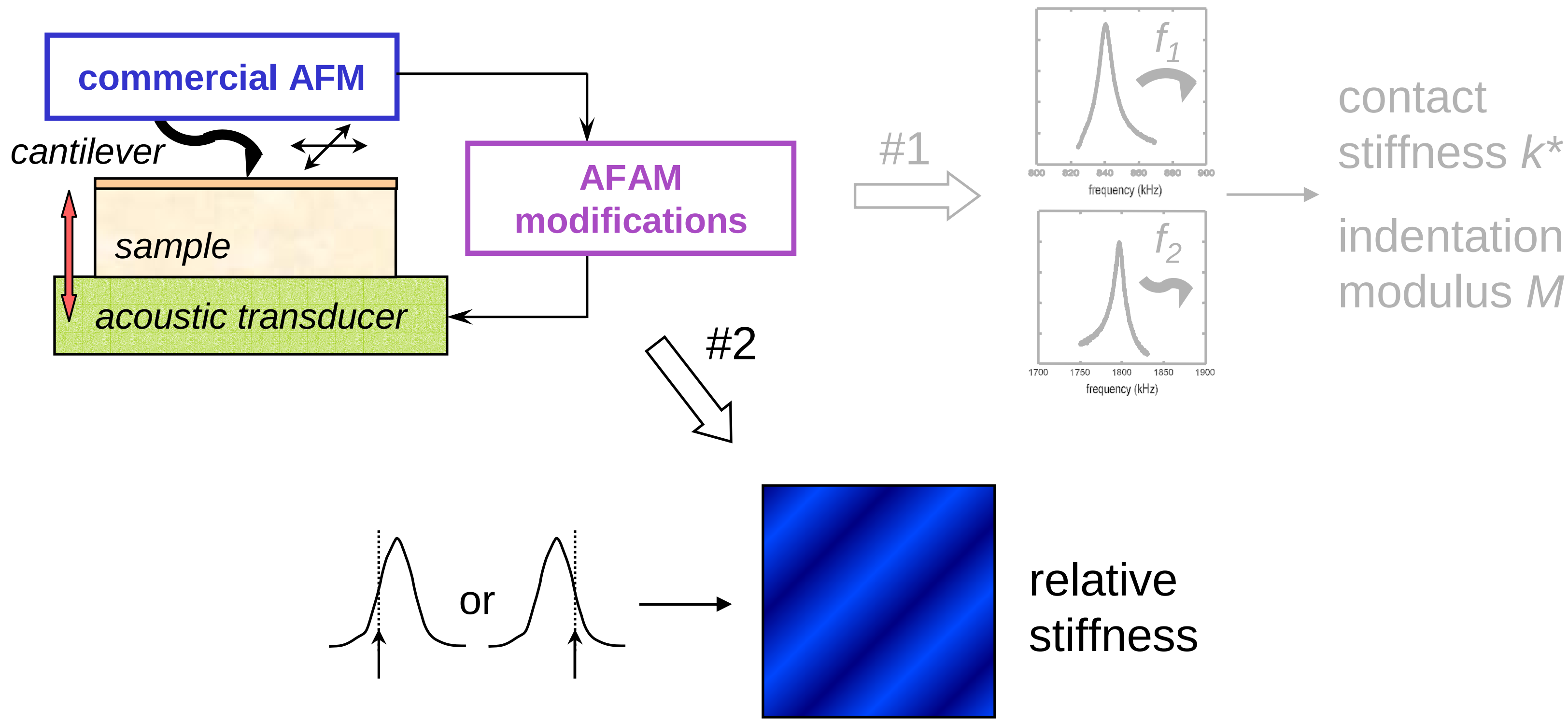
1. sweep frequency at fixed tip position → quantitative point measurement



Nanoscale Elastic Measurements with AFAM

1. sweep frequency at fixed tip position → quantitative point measurement

OR 2. scan tip position at fixed frequency → qualitative image



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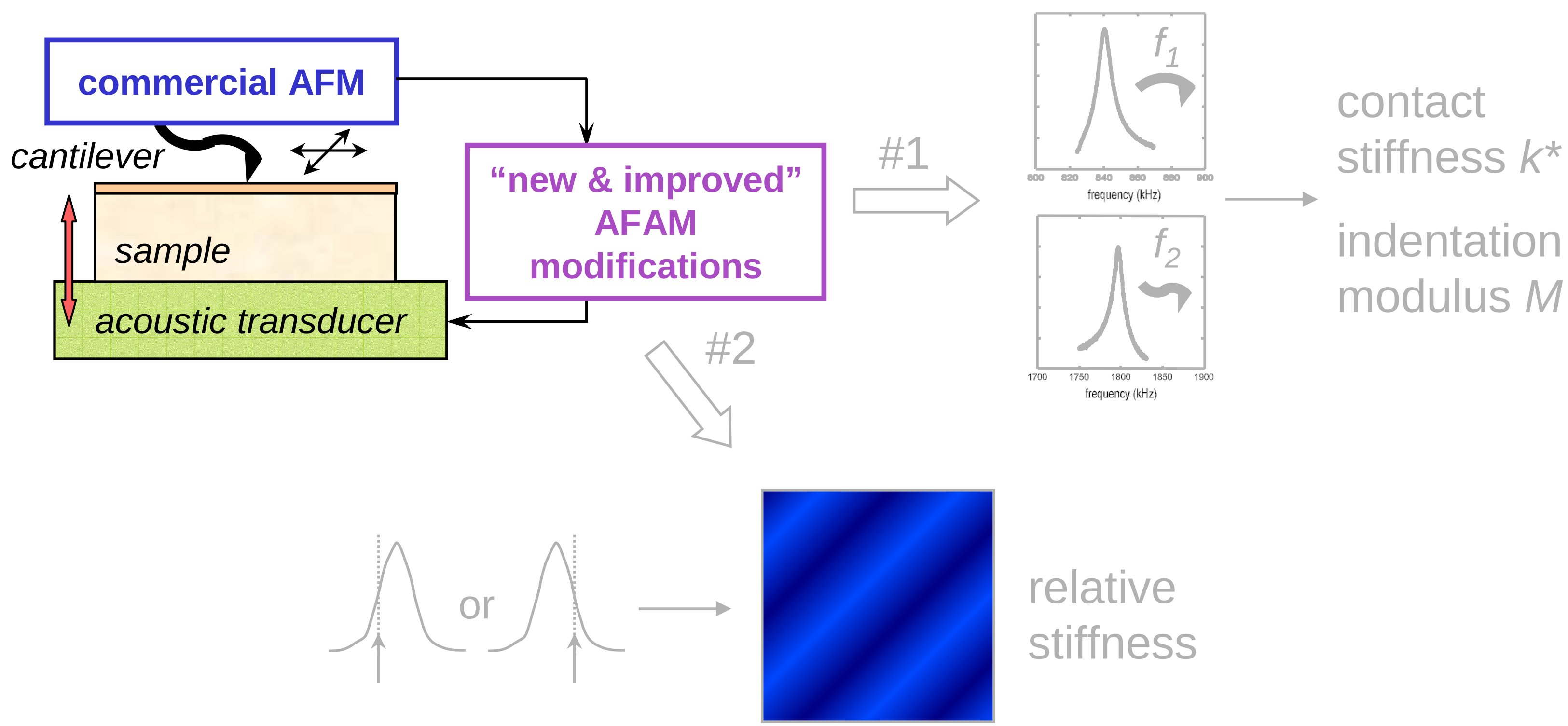
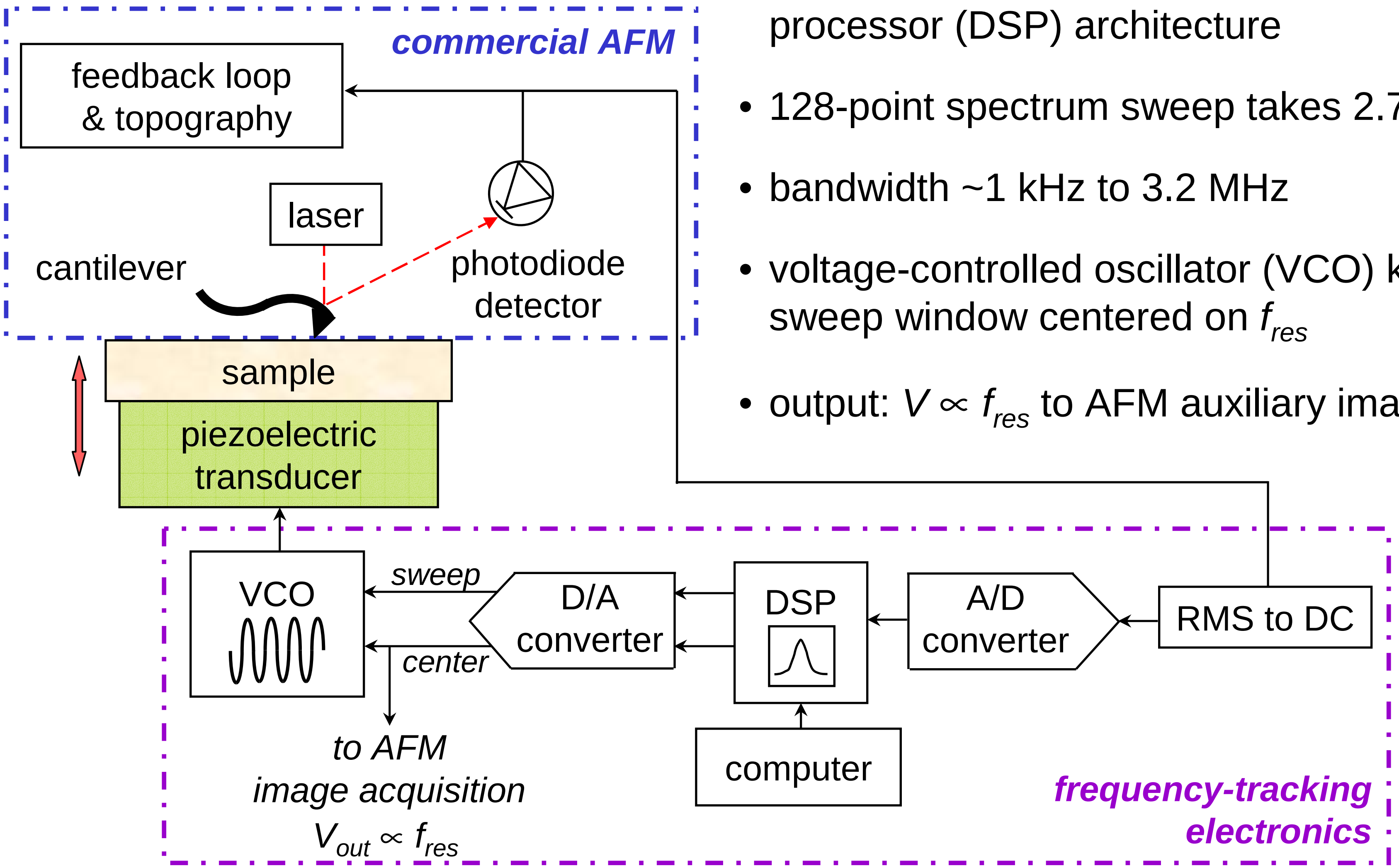


NEXT: <u>Quantitative imaging</u> of elastic properties

CHALLENGE: Do it <u>fast</u>!

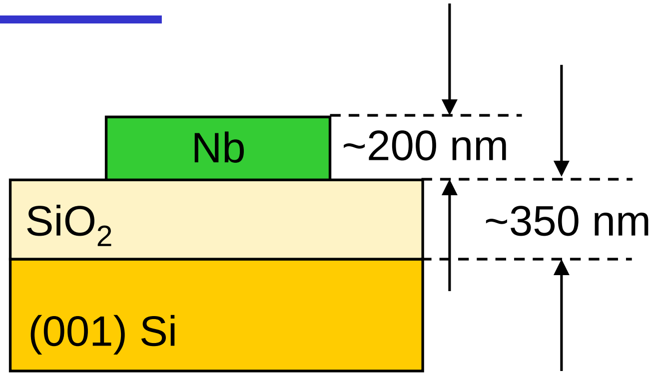
Contact-Resonance Frequency Imaging

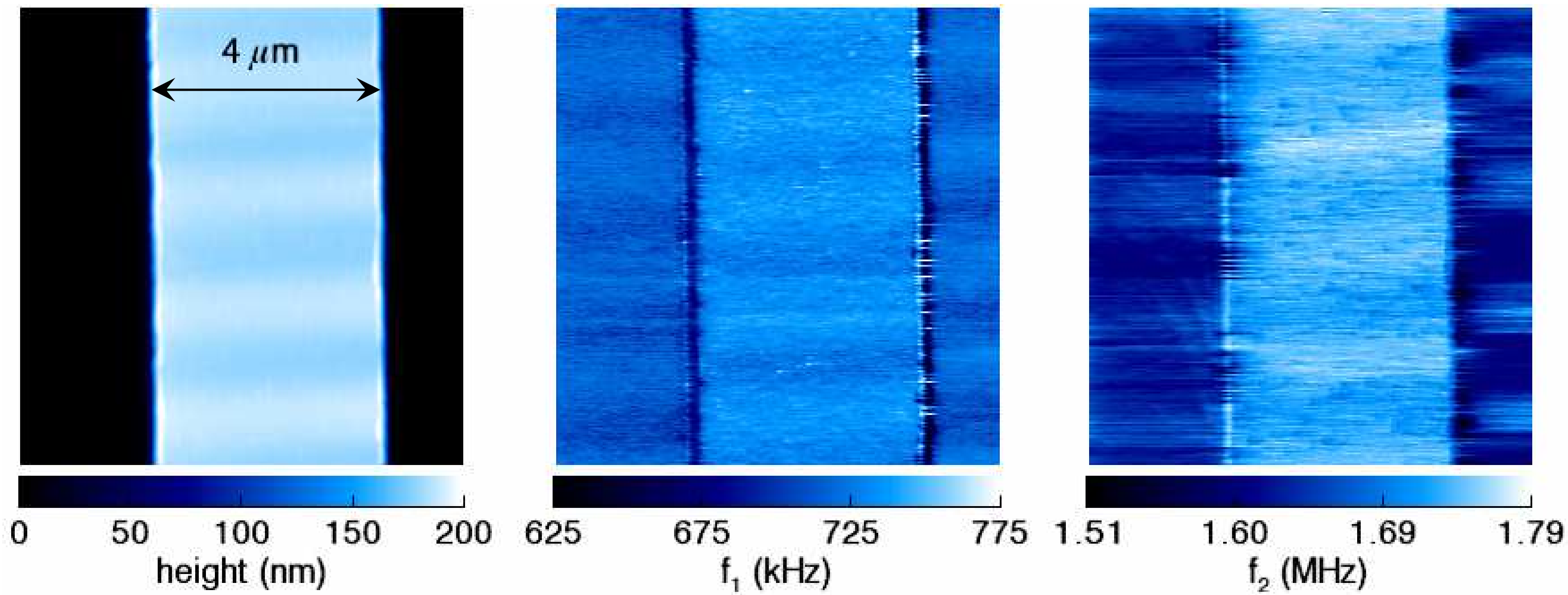


- electronics to track resonant frequency f_{res}
- 32-bit, floating-point digital signal processor (DSP) architecture
- 128-point spectrum sweep takes 2.7 ms
- bandwidth ~1 kHz to 3.2 MHz
- voltage-controlled oscillator (VCO) keeps sweep window centered on f_{res}
- output: $V \propto f_{res}$ to AFM auxiliary image port

Examples of Frequency Images

- 4 µm niobium “wire” on silica blanket film
- Image lowest 2 flexural (bending) modes
- ~22 minutes for each 256 x 256 image



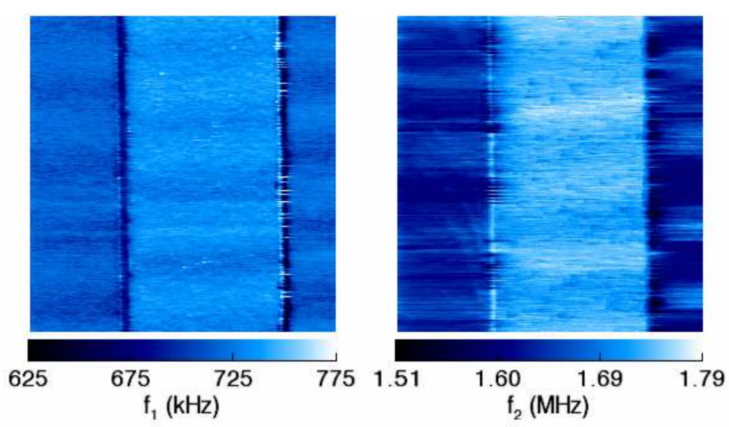


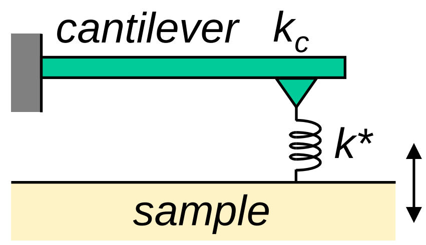
cantilever used (vendor specs):

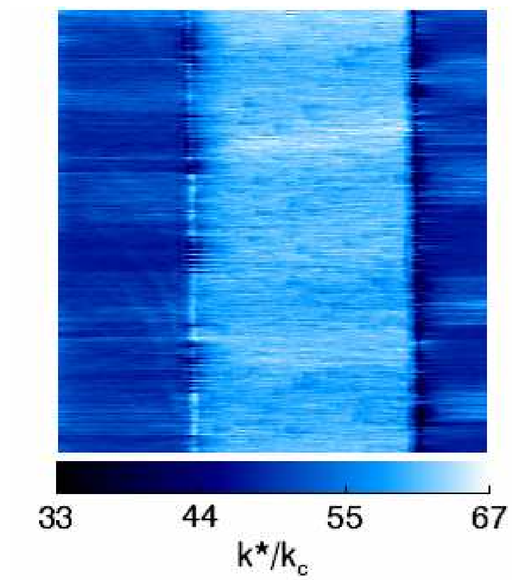
k_c = 47 N/m, L = 225 µm, W = 34 µm, t = 7.1 µm

Using Resonant-Frequency Images To Obtain Elastic-Property Information

- Contact stiffness: calculate k^*/k_c from f_1 and f_2 with beam-dynamics model







- Elastic modulus: requires data from reference material

$$E^*_{sample} = E^*_{ref}\left(\frac{k^*_{sample}/k_c}{k^*_{ref}/k_c}\right)^n \qquad \frac{1}{E^*} = \frac{1}{M_{tip}} + \frac{1}{M_{sample}} \qquad M = \frac{E}{1-\nu^2}$$

n=1 flat punch　　*n=3/2 Hertzian*

M_{tip} = 165 GPa for Si <100>

(isotropic)

E = Young's modulus

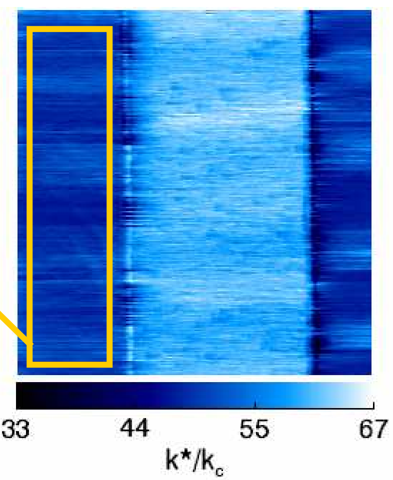
ν = Poisson's ratio

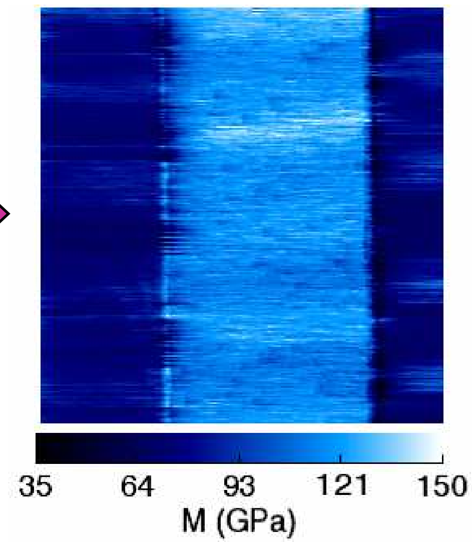
Calculating Modulus Maps from Contact-Stiffness Images

- Assume Hertzian contact mechanics
- Use “self-calibrating” method based on fixed-point measurements

$$E^*_{sample} = E^*_{ref}\left(\frac{k^*_{sample}/k_c}{\boxed{k^*_{ref}/k_c}}\right)^{3/2}$$

$$\frac{1}{E^*} = \frac{1}{M_{tip}} + \frac{1}{M_{sample}}$$





AFAM results for M (GPa)

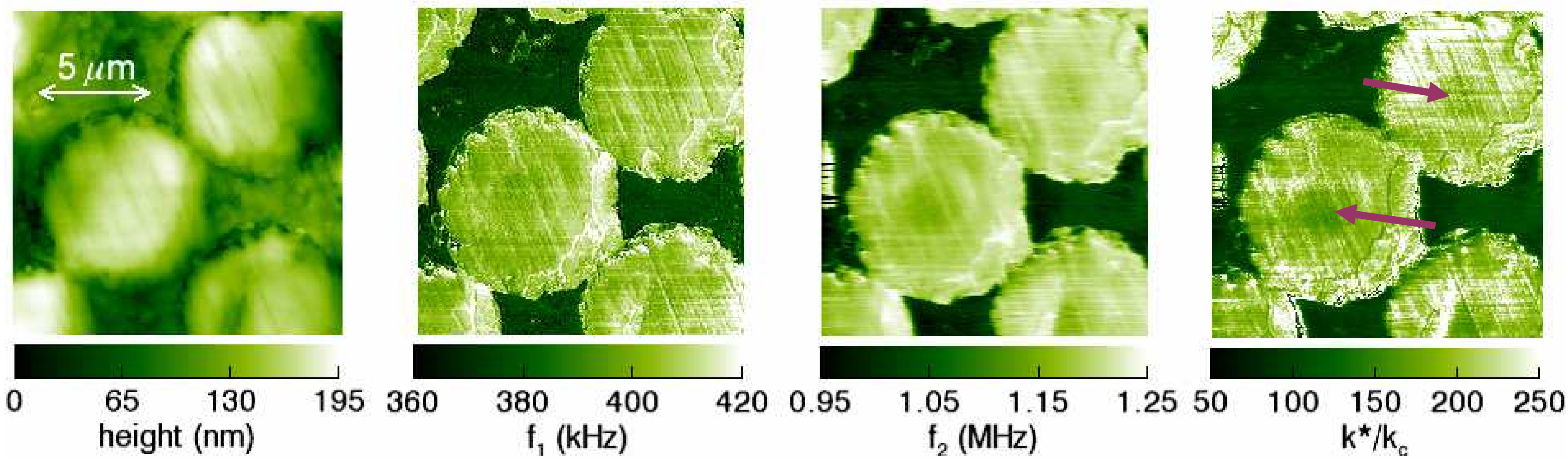
method	*film material*	
	SiO_2	Nb
fixed-point	75.1 ± 10.0	112.7 ± 15.0
image	75.5 ± 7.1	118.5 ± 7.1
literature	72-77	116-133

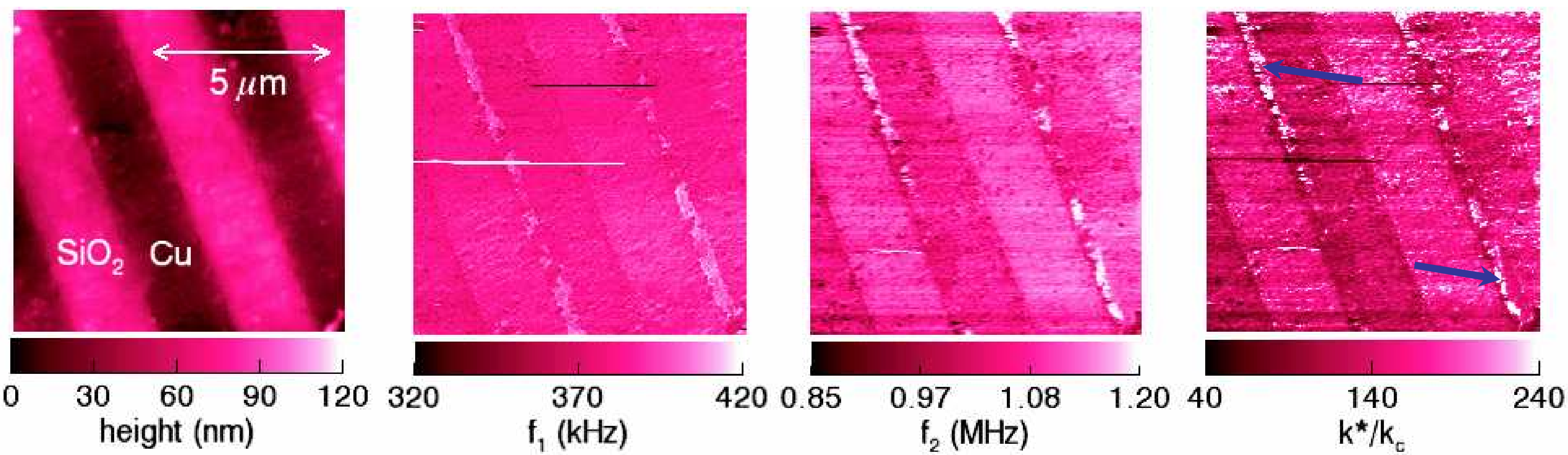
reference: fused silica, M = 74.9 GPa

Image values for M agree well with other data

Additional Flexural-Mode Images

epoxy/glass composite

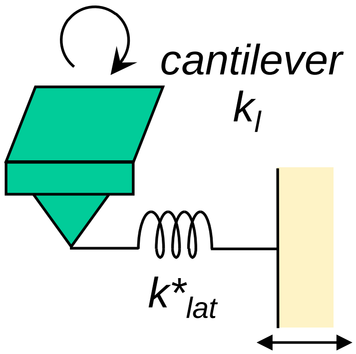


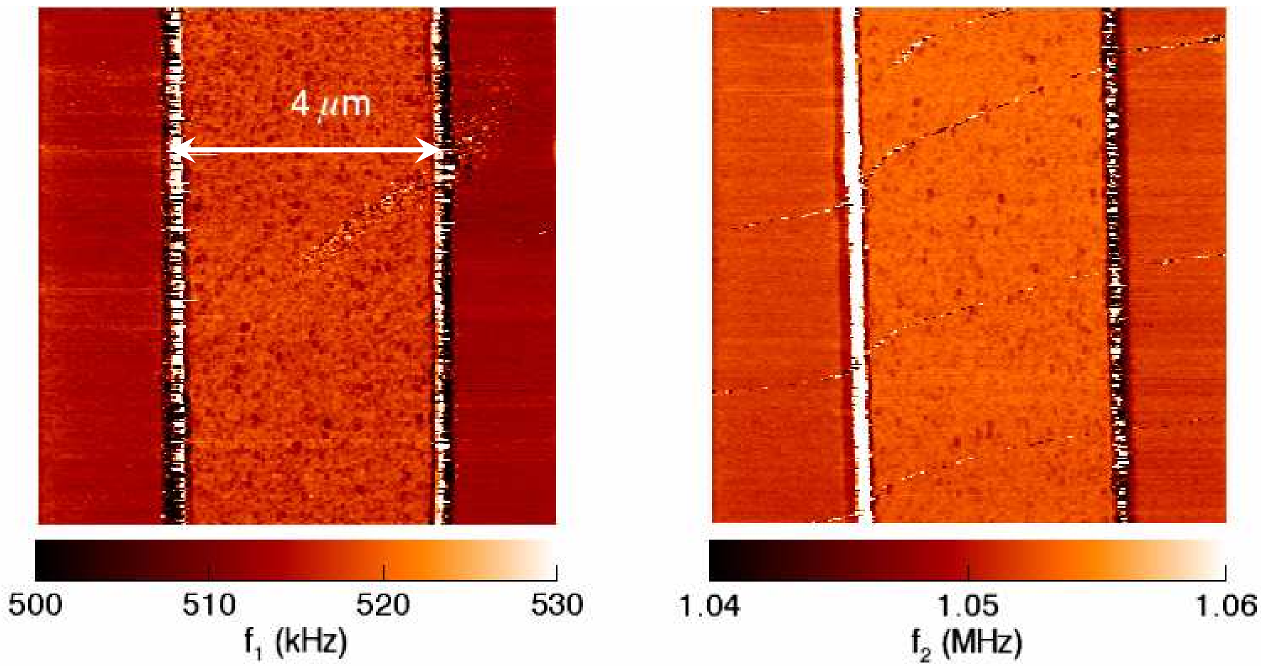


Cu/SiO$_2$ microelectronic test structure

Torsional Mode Images

- Detect torsional modes with left-to-right photodiode signal
- Obtain lateral (horizontal) contact stiffness k^*_{lat}
- Yields information about shear modulus $G = \dfrac{E}{2(1+\nu)}$
- Next: develop methods to calculate k^*_{lat} , G from f_1 *and* f_2





cantilever used (vendor specs):
k_c = 1 N/m, L = 448 μm, W = 51 μm, t = 3.5 μm

Summary and Conclusions

- AFAM uses contact-resonance modes of the AFM cantilever to nondestructively measure elastic properties.
- We have developed frequency-tracking electronics to obtain *nanoscale elastic-property maps* with AFAM.
- Flexural- and torsional-mode frequency images were shown to demonstrate the basic approach.
- Contact-stiffness images using flexural-mode images yield values of *M* in agreement with other results.
- Several issues (contact mechanics, calibration, etc.) must be further addressed for truly quantitative imaging.